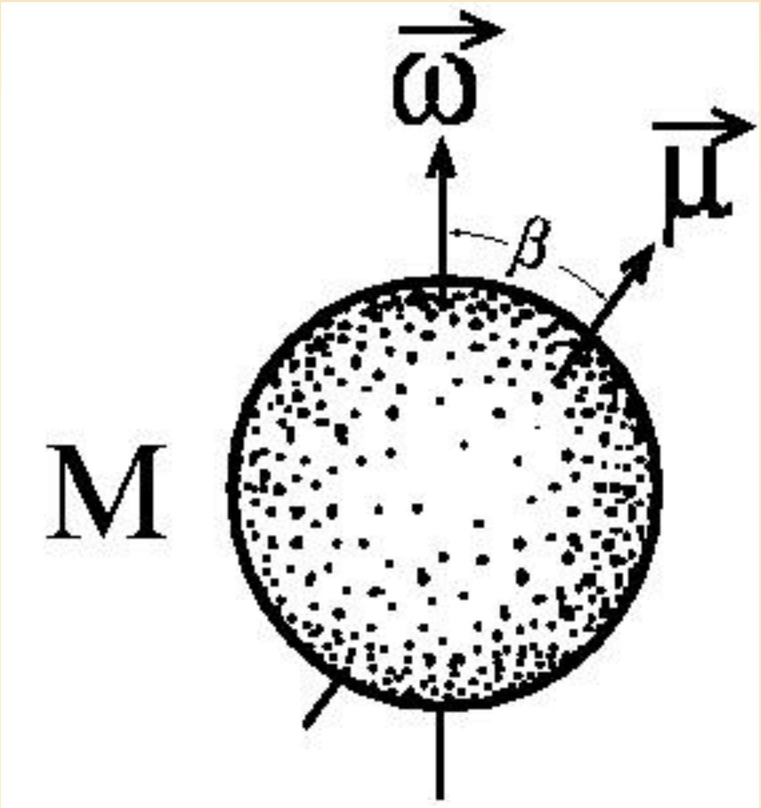
Accreting isolated neutron stars

Magnetic rotator



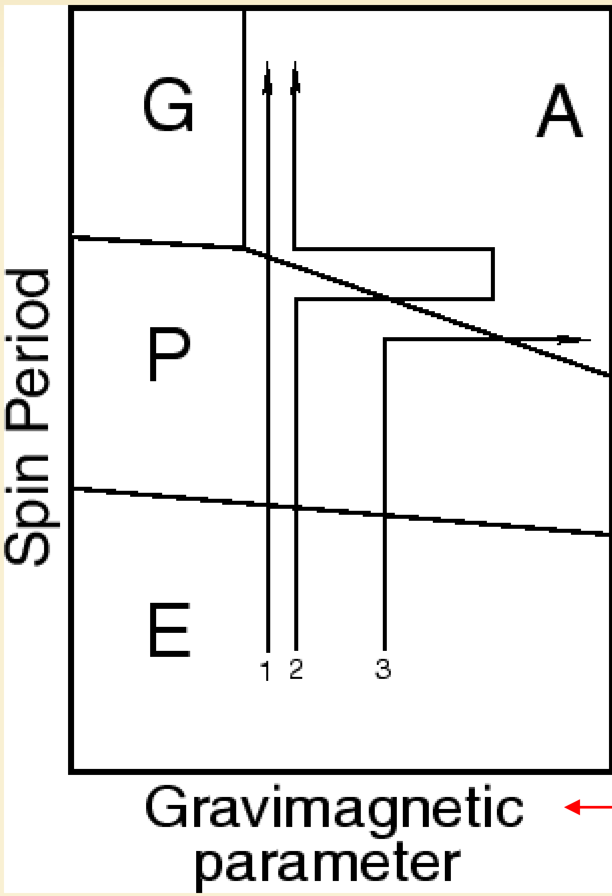
Observational appearances of NSs
(if we are not speaking about cooling)
are mainly determined by P, Pdot, V, B,
(also, probably by the inclination angle β),
and properties of the surrounding medium.
B is not evolving significantly in most cases,
so it is important to discuss spin evolution.

Together with changes in B (and β)
one can speak about
magneto-rotational evolution

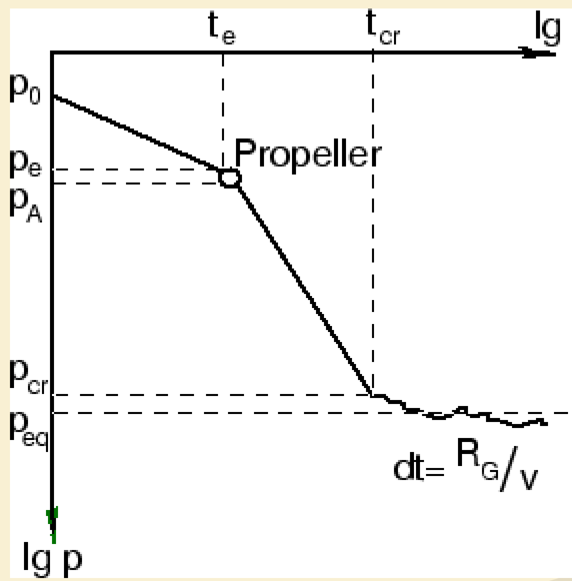
We are going to discuss the main stages of this evolution, namely:
Ejector, Propeller, Accretor, and *Georotator*
following the classification by Lipunov

Evolution of neutron stars: rotation + magnetic field

Ejector → Propeller → Accretor → Georotator



1 – spin down
2 – passage through a molecular cloud
3 – magnetic field decay



[astro-ph/0101031]

Mdot/μ^2

See the book by Lipunov (1987, 1992)

Accreting isolated neutron stars

Why are they so important?

- Can show us how old NSs look like

1. Magnetic field decay
2. Spin evolution

- Physics of accretion at low rates
- NS velocity distribution
- New probe of NS surface and interiors
- ISM probe

Critical periods for isolated NSs

$$P_E(E \rightarrow P) \simeq 10\,\mu_{30}^{1/2}\,n^{-1/4}\,v_{10}^{1/2}\ \mathrm{s}$$

Transition from Ejector to Propeller (supersonic)

$$t_E \simeq 10^9\,\mu_{30}^{-1}\,n^{-1/2}\,v_{10}\ \mathrm{yr}$$

Duration of the ejector stage

$$P_A(P \rightarrow A) \simeq 420\,\mu_{30}^{6/7}\,n^{-3/7}\,v_{10}^{9/7}\ \mathrm{s}$$

Transition from supersonic Propeller to subsonic Propeller or Accretor

$$P_{eq} = 2.6 \times 10^3\,v_{(t)10}^{-2/3}\,\mu_{30}^{2/3}\,n^{-2/3}\,v_{10}^{13/3}\ \mathrm{s}$$

A kind of equilibrium period for the case of accretion from turbulent medium

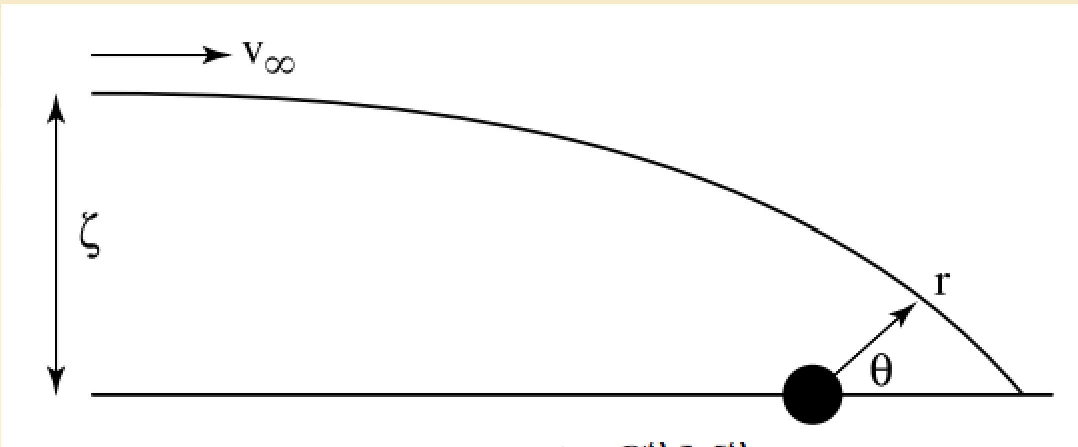
$$v < 410\,n^{1/10}\,\mu_{30}^{-1/5}\ \mathrm{km\,s^{-1}}$$

Condition for the Georotator formation (instead of Propeller or Accretor)

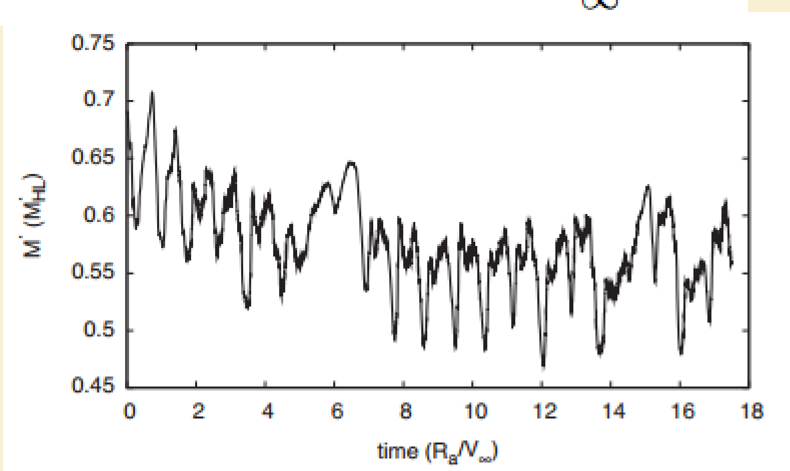
(see, for example, astro-ph/9910114)

Accretion dynamics

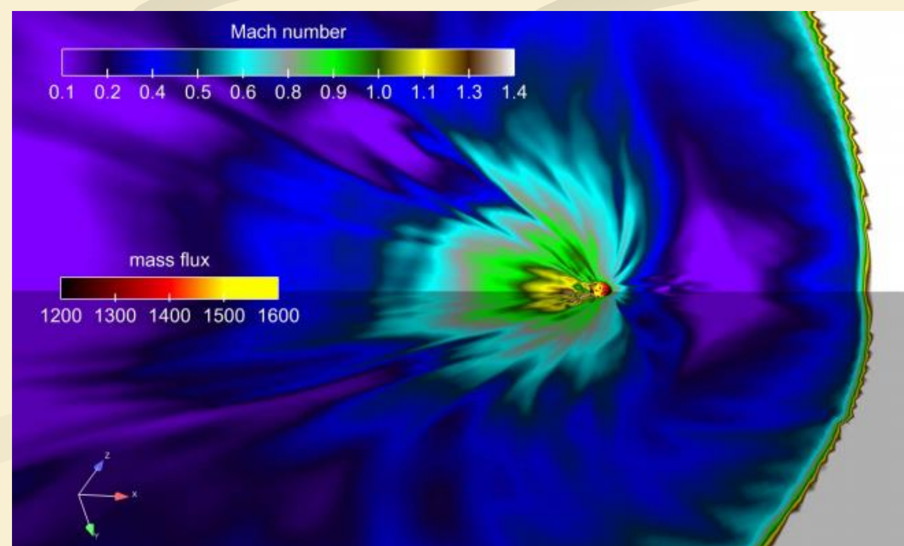
Bondi-Hoyle-Littleton accretion (astro-ph/0406166)



$$\dot{M}_{\rm HL} = \pi \zeta_{\rm HL}^2 v_\infty \rho_\infty = \frac{4\pi G^2 M^2 \rho_\infty}{v_\infty^3}$$



Recently BHL accretion for non-magnetized accretors have been studied in 1204.0717. Still, resolution in 3D is not high enough.



Expected properties

1. **Accretion rate**

An upper limit can be given by the Bondi formula:
Mdot = $\pi R_G^2 \varrho v$, $R_G \sim v^{-2}$
Mdot = 10^{11} g/s (v/10 km/s) $^{-3}$ n
L=0.1 Mdot $c^2 \sim 10^{31}$ erg/s

However, accretion can be smaller due to the influence of a magnetosphere of a NS (see numerical studies by Toropina et al. 1111.2460).

2. **Periods**

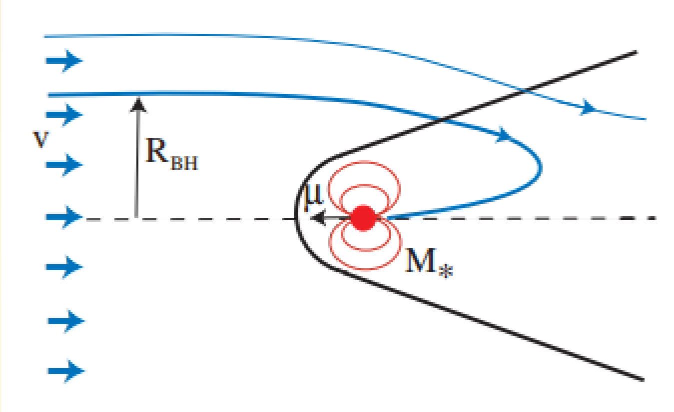
Periods of old accreting NSs are uncertain, because we do not know evolution well enough.

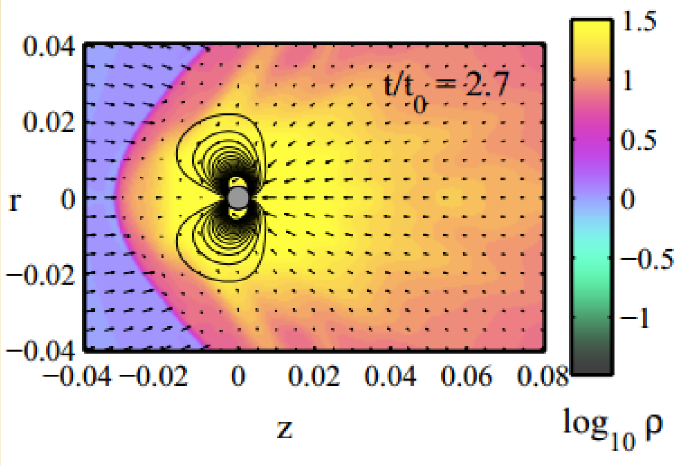
$$p_A = 2^{5/14}\pi(GM)^{-5/7}(\mu^2/\dot{M})^{3/7} \simeq$$

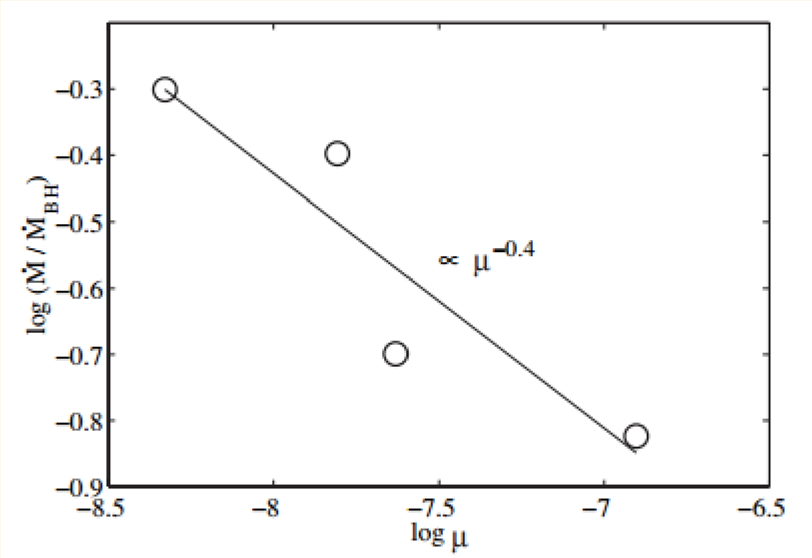
$R_A = R_{co}$

$$300\,\mu_{30}^{6/7}(v/10\,\mathrm{km\,s^{-1}})^{9/7}n^{-3/7}\ \mathrm{s}.$$

Reduction of the accretion rate







Surface accretion accretion rate can be much reduced due to the presence of large magnetosphere.

1111.2460

Subsonic propeller

Even after $R_{co}>R_A$ accretion can be inhibited.
This have been noted already in the pioneer papers by Davies et al.

Due to rapid (however, subsonic) rotation a hot envelope is formed around the magnetosphere. So, a new critical period appear.

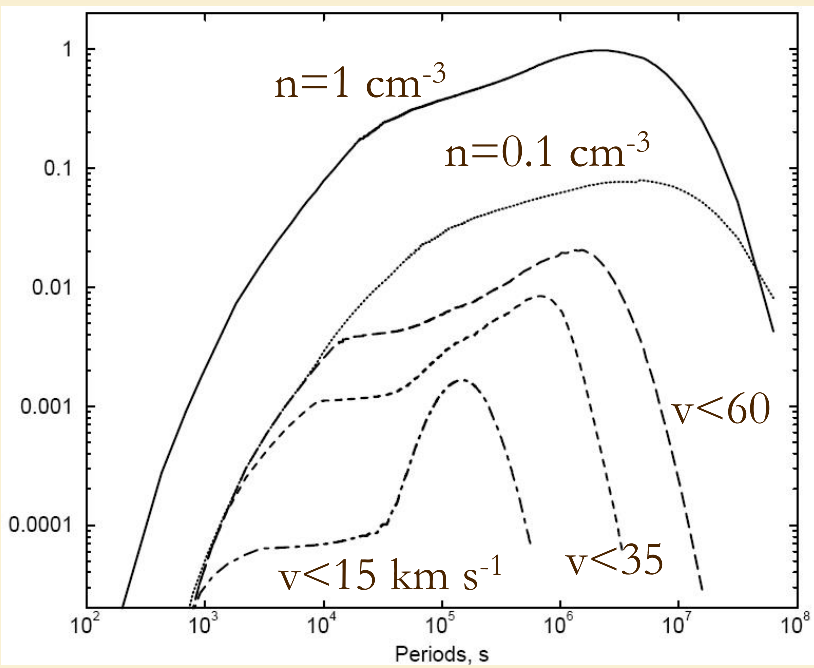
$$P_{\rm br} \simeq 450\,\mu_{30}^{16/21}\,\dot{M}_{15}^{-5/7}\,m^{-4/21}\ {\rm s.}$$

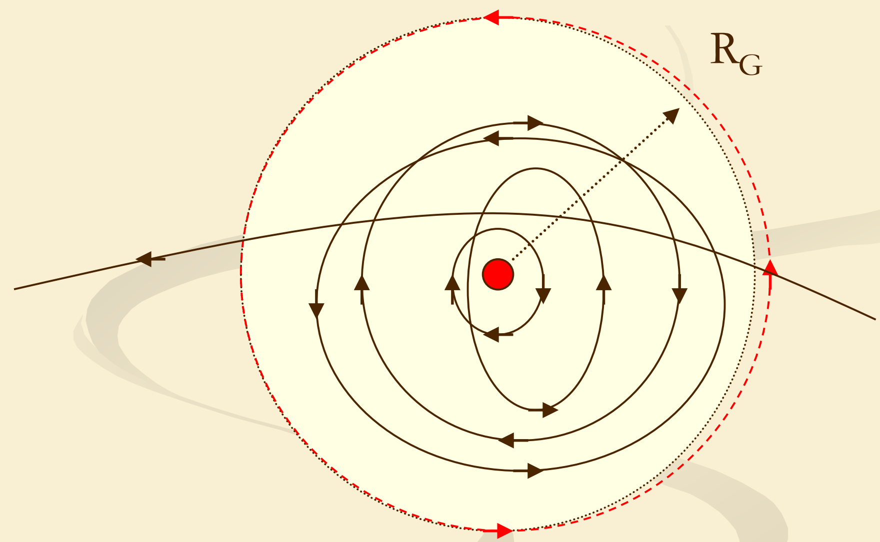
(Ikhsanov astro-ph/0310076)

If this stage is realized (inefficient cooling) then
- accretion starts later
- accretors have longer periods

Equilibrium period

Interstellar medium is turbulized. If we put a non-rotating NS in the ISM, then because of accretions of turbulized matter it'll start to rotate.
This clearly illustrates, that a spinning-down accreting isolated NS in a realistic ISM should reach some equilibrium period.





[A&A 381, 1000 (2002)]

$$P_{eq} = 2.6 \times 10^3 \, v_{(t)10}^{-2/3} \, \mu_{30}^{2/3} \, n^{-2/3} \, v_{10}^{13/3} \;\; \mathrm{s}$$

A kind of equilibrium period for the case of accretion from turbulent medium

Disc formation

Accretion of turbulized matter can result in a transient accretion disc formation.

$$j_t = v_t(R_G) \cdot R_G = v_t(R_t) R_t^{-1/3} R_G^{4/3}$$

If j_t is larger than the keplerian momentum at the magnetospheric boundary (Alfven radius) then a disc can be formed.

$$j_K = v_K(R_A) \cdot R_A$$

Might happen for low magnetic fields
and low spatial velocities.
More prominent for accreting isolated BHs.

See, e.g., astro-ph/0108503

Expected properties-2

3. Temperatures

Depend on the magnetic field. The size of polar caps depends on the field and accretion rate: $\sim R\,(R/R_A)^{1/2}$

4. Magnetic fields

Very uncertain, as models of the field decay cannot give any solid predictions for very long time scales (billions of years).

5. Flux variability.

Due to fluctuations of matter density and turbulent velocity in the ISM it is expected that isolated accretors are variable on a time scale $\sim R_G/v \sim$ days - months

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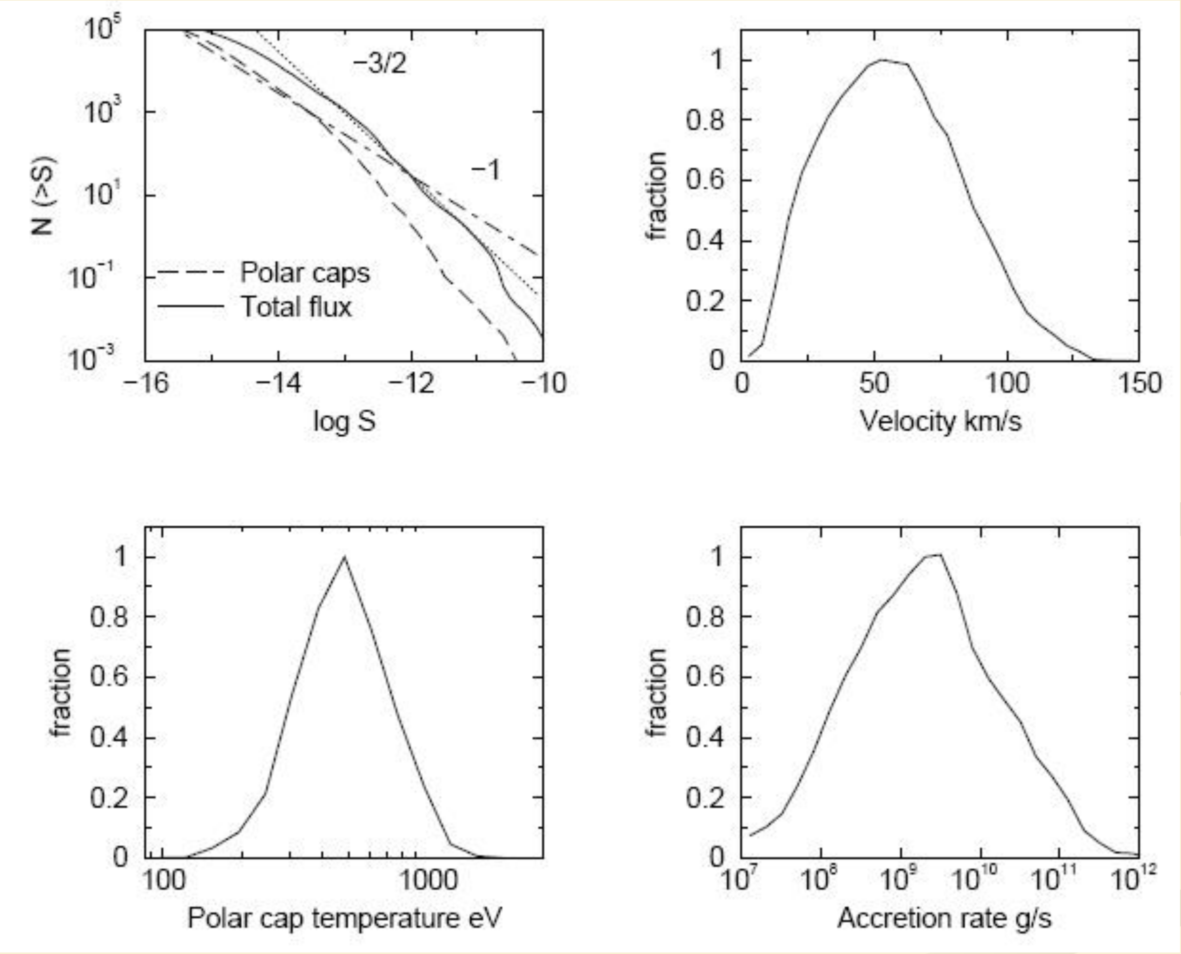
Still, isolated accretors are expected to be numerous at low fluxes (their total number in the Galaxy is large than the number of coolers of comparable luminosity). They should be hotter than coolers, and have much longer spin periods.

Properties of accretors



In the framework of a simplified model (no subsonic propeller, no field decay, no accretion inhibition, etc.) one can estimate properties of isolated accretors.

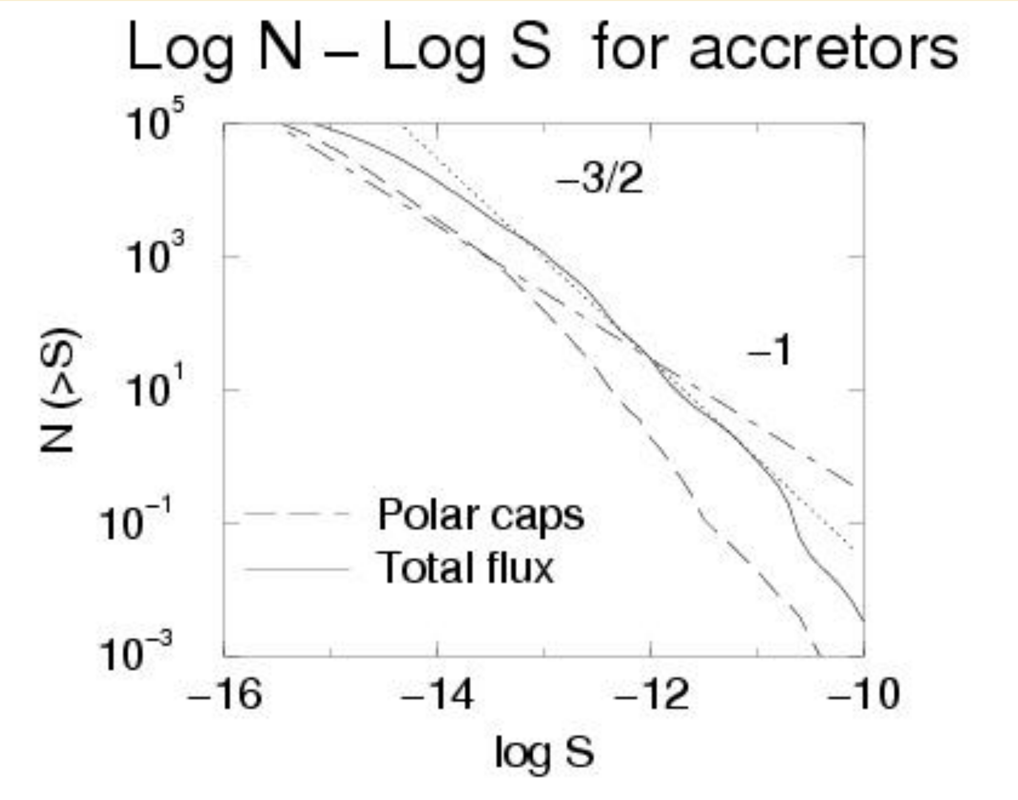
Slow, hot, dim, numerous at low fluxes ($<10^{-13}$ erg/cm^2/s)

Reality is more uncertain.

(astro-ph/0009225)

Accreting isolated NSs

At small fluxes $<10^{-13}$ erg/s/cm^2 accretors can become more abundant than coolers. Accretors are expected to be slightly harder: 300-500 eV vs. 50-100 eV. Good targets for eROSITA!



From several hundreds up to several thousands objects at fluxes about few $\cdot 10^{-14}$, but difficult to identify.

Monitoring is important.

Also isolated accretors can be found in the Galactic center (Zane et al. 1996, Deegan, Nayakshin 2006).

astro-ph/0009225

Where and how to look for

As sources are dim even in X-rays,
and probably are extremely dim in other bands
it is very difficult to find them.

In an optimistic scenario they outnumber cooling NSs at low fluxes.
Probably, for ROSAT they are to dim.
We hope that eROSITA will be able to identify accreting INSs.

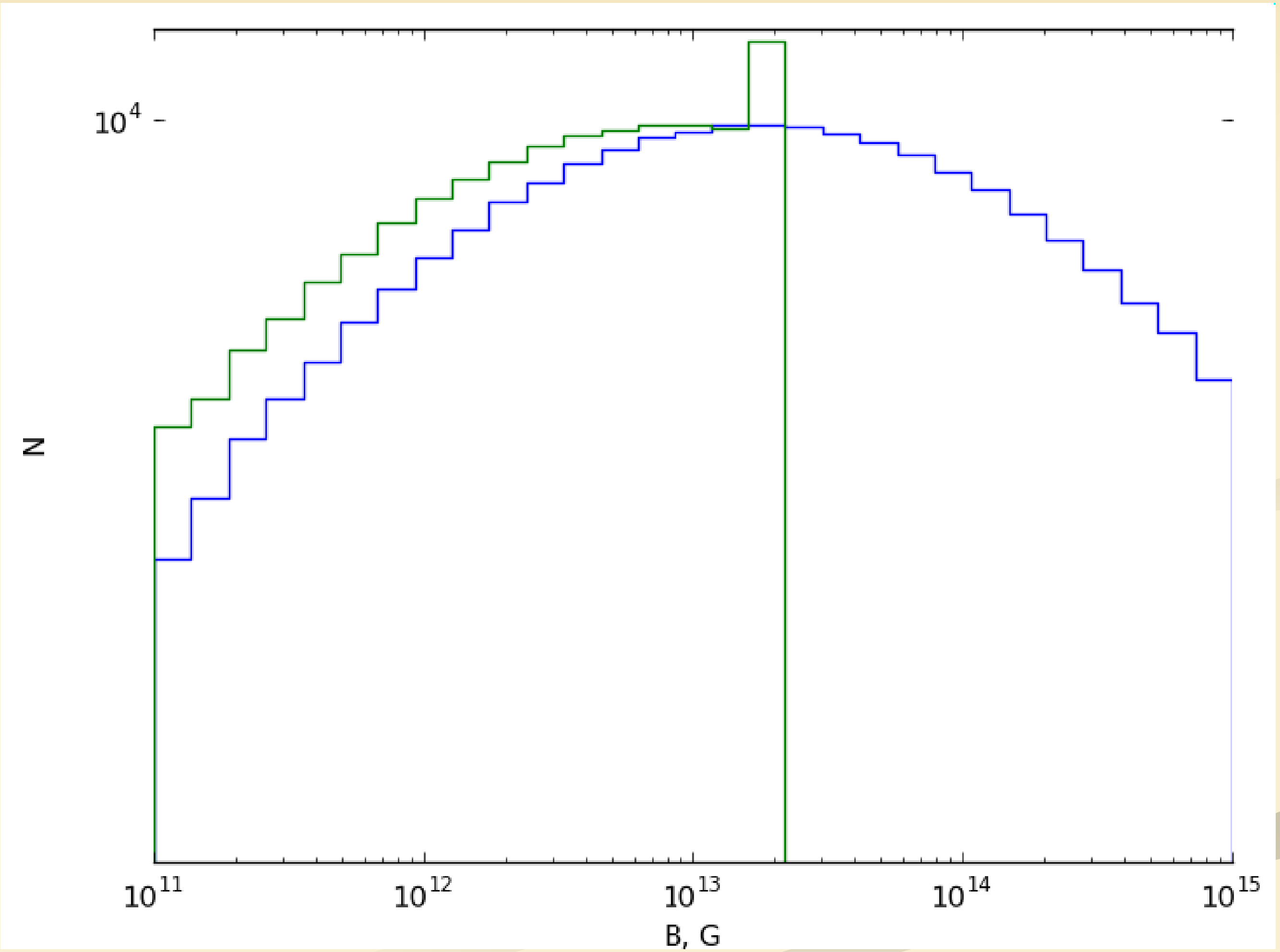
Their spatial density at fluxes ~10^{-15} erg/cm^2/s is expected to be ~few per sq.degree in directions close to the galactic plane.

It is necessary to have an X-ray survey at ~100-500 eV with good resolution.

In a recent paper by Muno et al.the authors put interesting limits on the number of unidentified magnetars. The same results can be rescaled to give limits on the M7-like sources.

“Decayed” field distribution

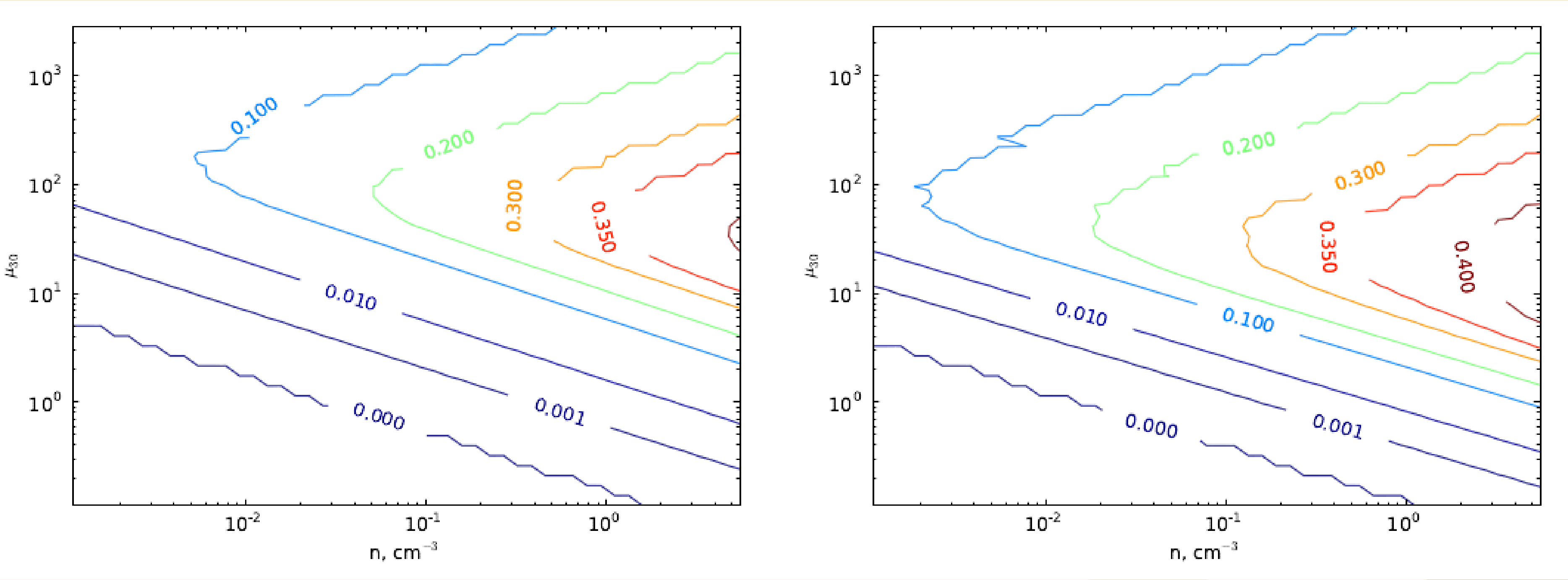
We assume the field to be constant, but as an initial we use the “decayed” distribution, following Popov et al. 2010.



Boldin, Popov 2010

Simple semianalytical model

Fraction of accretors for different magnetic fields and ISM density.
Kick velocity distribution is taken following Arzoumanian et al. (2002).



With subsonic

Without subsonic

Boldin, Popov 2010

Individual tracks

Individual tracks in the semianalytical model. Clearly, even with long subsonic propeller stage highly magnetized NSs (like the M7) can become accretors relatively soon.

Track	n, cm^{-3}	μ_{30}	v_{10}	$\tau_{\rm E}$	$P_{\rm E}$, s	$\tau_{\rm P}$	$P_{\rm P}$, s	$\tau_{\rm ssP}$	$P_{\rm break}$, s
Track I	0.5	1	5	0.419	16.051	0.423	3.163×10^3	0.850	2.278×10^6
Track II	0.5	1	20	–	–	–	–	–	–
Track III	0.5	1	40	–	–	–	–	–	–
Track IV	0.5	10	5	0.042	50.758	0.042	2.276×10^4	0.067	1.317×10^7
Track V	0.5	10	20	0.168	101.517	0.170	1.353×10^5	0.651	2.568×10^8
Track VI	0.5	10	40	0.163	100.091	0.169	1.523×10^5	Georotator	
Track VII	2.0	1	5	0.209	11.350	0.212	1.746×10^3	0.370	8.464×10^5
Track VIII	2.0	1	20	0.838	22.700	0.854	1.038×10^4	–	–
Track IX	2.0	1	40	–	–	–	–	–	–
Track X	2.0	10	5	0.021	35.892	0.021	1.257×10^4	0.030	4.892×10^6
Track XI	2.0	10	20	0.084	71.783	0.085	7.469×10^4	0.264	9.541×10^7
Track XII	2.0	10	40	0.103	79.442	0.106	1.077×10^5	Georotator	

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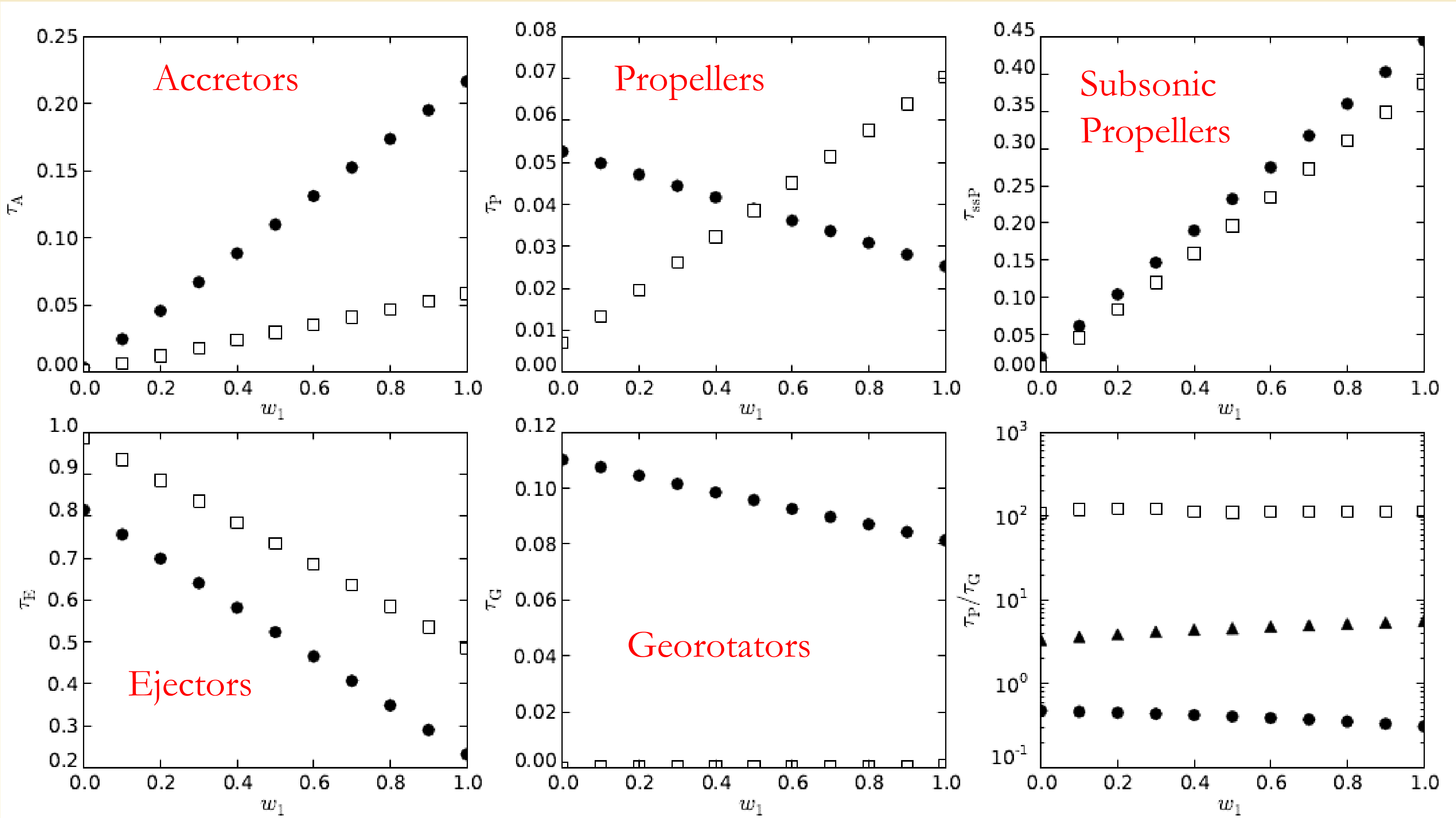
Final distributions

Filled symbols – “decayed distribution”.

Open squares – delta-function μ_{30}=1.



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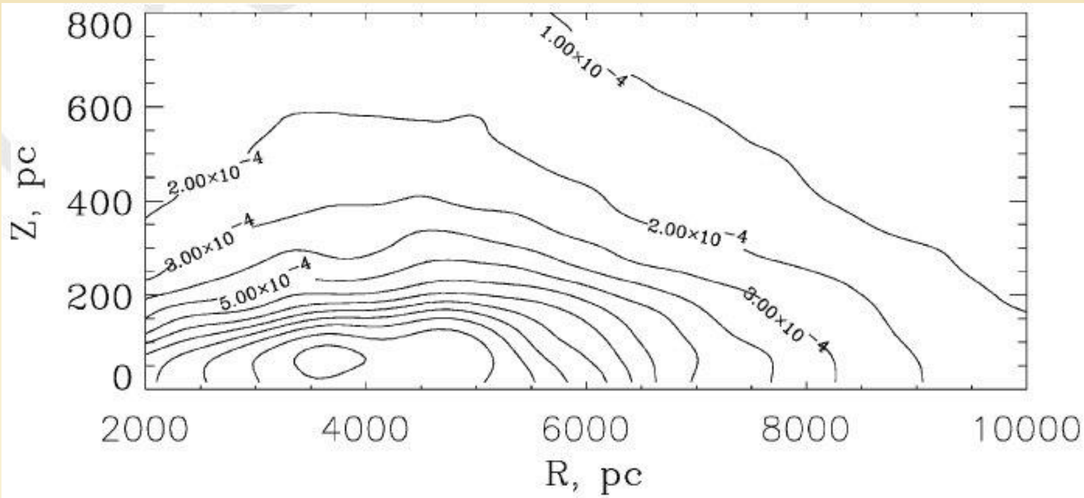
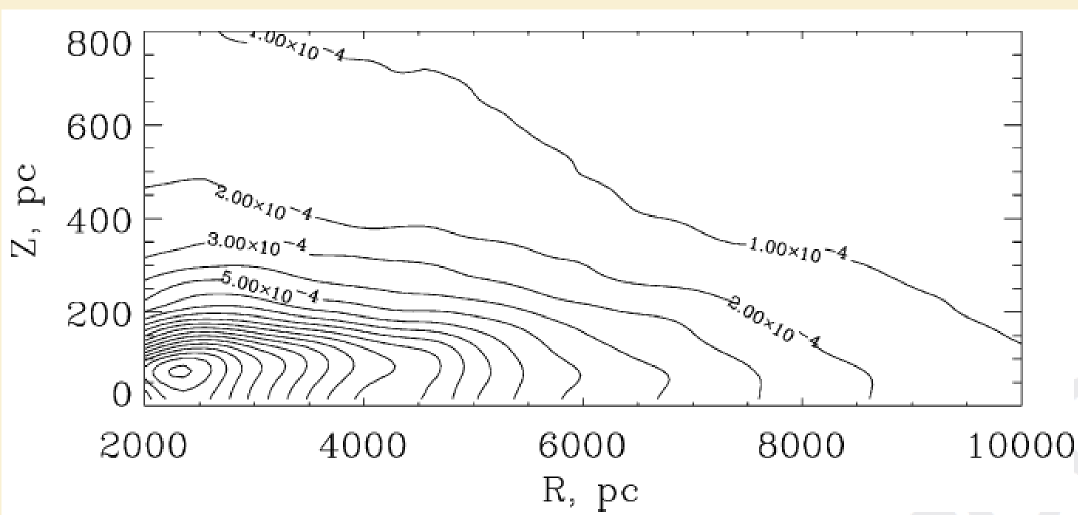
Spatial density of NSs





In both models N=5 10^8.
Kick: ACC02.
Potential: Paczynski 1990

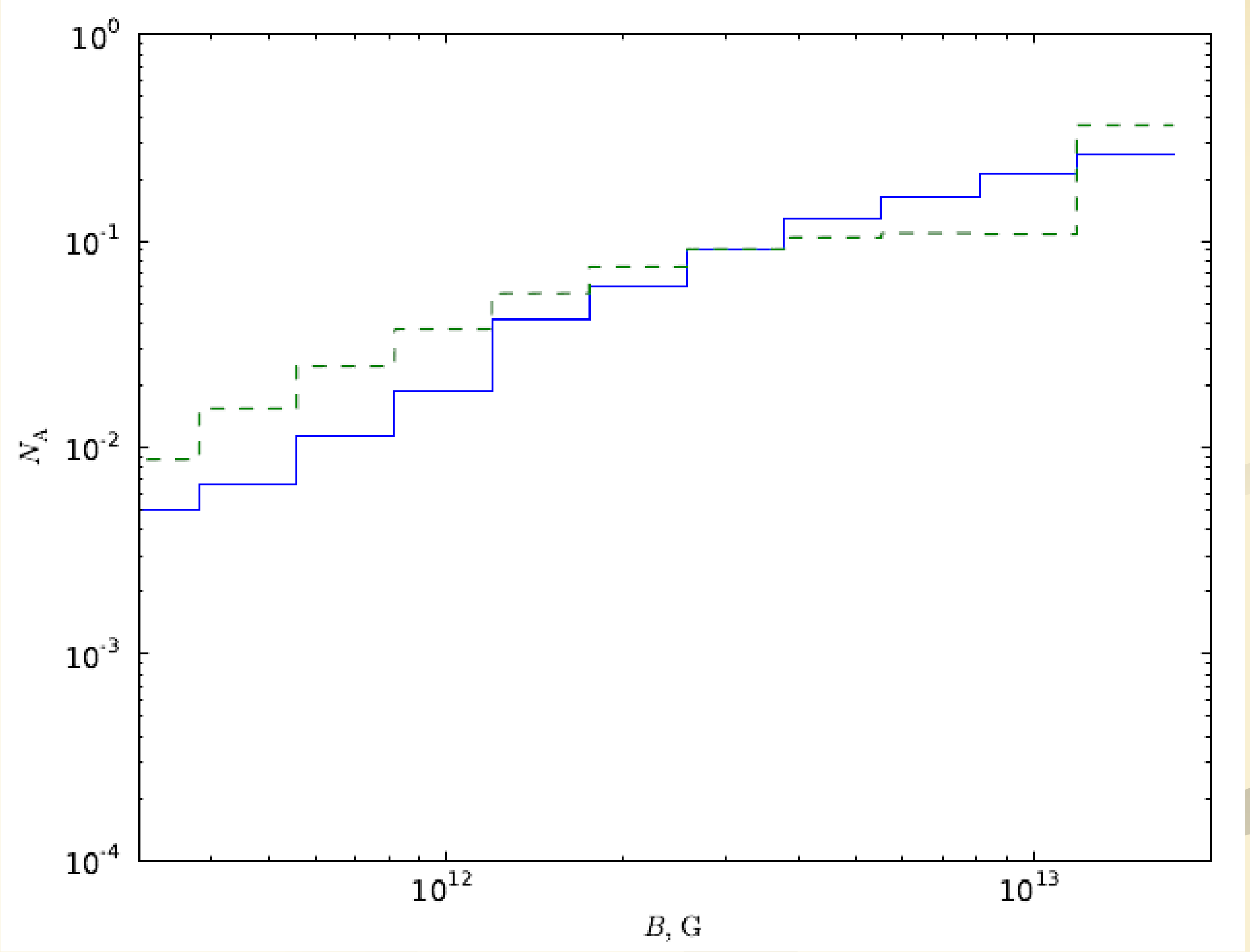
NS formation rate is assumed to be proportional to the square of the ISM density at the birthplace.

Formation rate is proportional to [exp(−z/75 pc) exp(−R/4 kpc)].

astro-ph/0305599

Who forms accretors?

NSs with stronger fields form more accretors, unless their field *and* velocities are so high, that they become Georotators.



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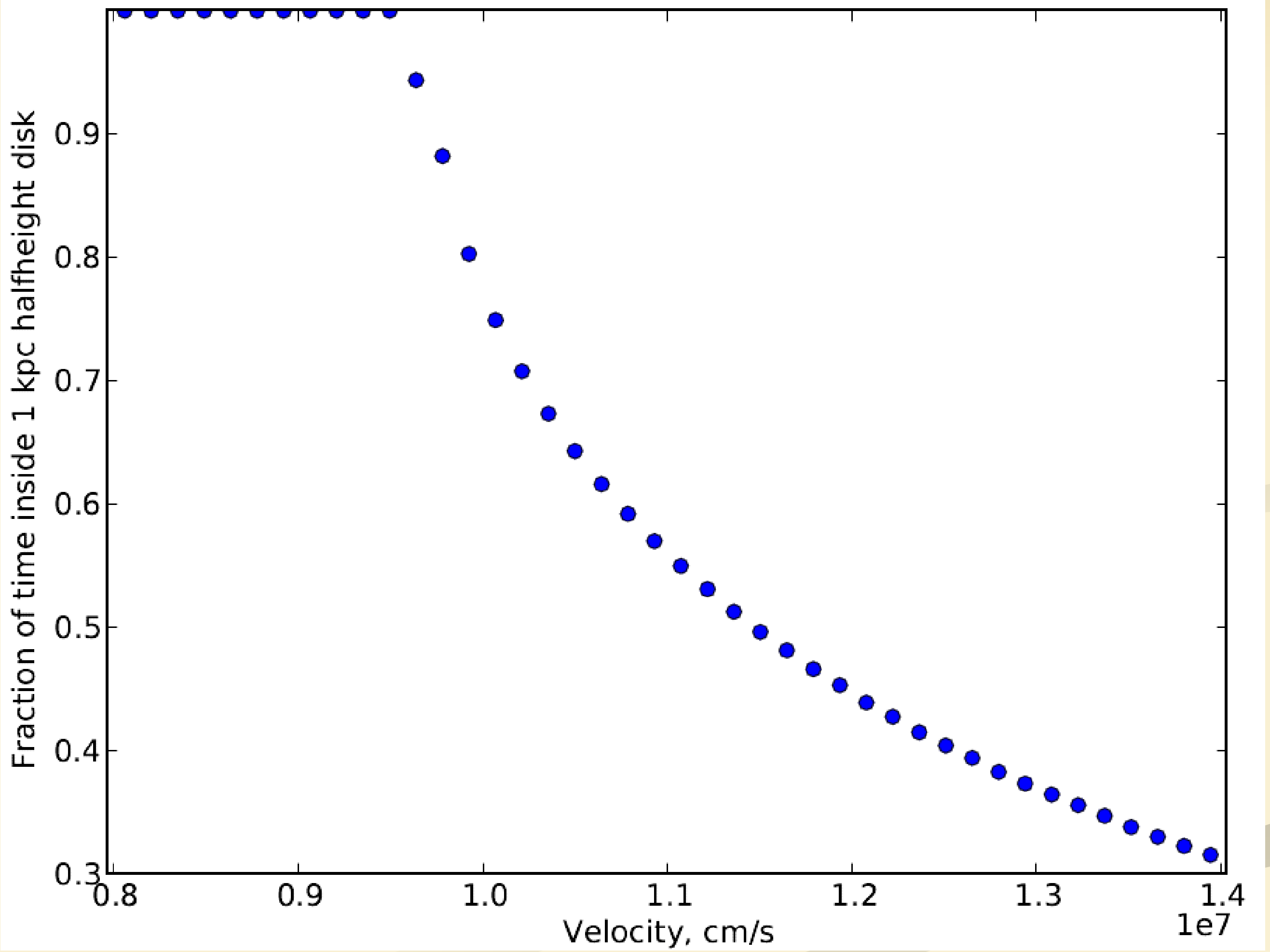
Running out of the Galaxy

2/3 of NSs leave
the Galaxy.
Mostly, they stay
as Ejectors, or become
Georotators.



In the solar vicinity
fractions of INSs at
different evolutionary
stages are:

- Ejectors: 18-20%
- Propellers: negligible
- subsonic P.: 40-45%
- Accretors: 35-40%
- Georotators: negligible

Boldin, Popov 2010

Some conclusions

- Highly magnetized INS (as the M7) can become Accretors even taking into account long subsonic Propeller stage.

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  - Ejectors: 18-20%
  - Propellers: negligible
  - subsonic P.: 40-45%
  - Accretors: 35-40%
  - Georotators: negligible

Boldin, Popov 2010

Settling accretion onto INSs

At low X-ray luminosities the captured matter, heated in the bow-shock, has no time to cool down and remains hot, which prevents it from entering the NS magnetosphere via Rayleigh-Taylor (RT) instability.

$$\dot{M}_{\rm x} \simeq (t_{\rm ff}/t_{\rm cool})^{1/3}\dot{M}_{\rm B}$$

$$\dot{M}_{\rm B} = \rho_\infty v(\pi R_{\rm G}^2) \sim 1.9\times 10^9\, n\, v_7^{-3}\,{\rm g\,s^{-1}}$$

$$t_{\rm ff} = R^{3/2}/\sqrt{GM}.$$

$$t_{\rm cool} = 3\times 10^8 \left(\frac{R_{\rm A}}{10^{10}{\rm cm}}\right)\times \left(\frac{L_{\rm x}}{10^{30}{\rm erg\,s^{-1}}}\right)^{-1}\frac{f(u)}{0.01}(1+X)^{-1}\,{\rm s}.$$

$$f(u) = u_{\rm r}/u_{\rm ff} < 1$$

$$R_{\rm A} \approx 2.2\times 10^{10} L_{30}^{-2/9}\mu_{30}^{16/27}\,{\rm cm}.$$

Thus, steady accretion luminosity is expected to be low, however, flares with duration hours-day are possible. Maximum luminosity can be ~10^{31} erg/s.

1412.4066

Papers to read

- Treves et al. PASP 112, 297 (2000)
- Popov et al. ApJ 530, 896 (2000)
- Popov, Prokhorov Physics Uspekhi 50, 1123 (2007) Ch. 5.4
- Boldin, Popov MNRAS vol. 407, pp. 1090-1097 (2010)
- Edgar astro-ph/0406166
- Popov et al. MNRAS 487, 2817 (2015)